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A confusion of tongues or the art of aggregating indicators—Reflections on four projective methodologies on sustainability measurement

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ABSTRACT

To achieve consensus on the broad term sustainability abstractness is required. In turn, to take sustainability as an action guiding mandate for implementation it needs to be concrete. The paper seeks to bridge the gap from theory of sustainability to practical application by implementing four different methods, i.e. social cost analysis, ecological footprint analysis, exergy approach and multi criteria decision analysis (MCDA). These methods will be exemplarily applied for sustainability analysis of household heating technologies focusing on wood pellet boilers, wood chip fired district heating stations and natural gas fired condensing boilers. Based on the integrated assessment of exemplary heat supply technologies a critical outlook on the four projective approaches is given.

Contents

1. Sustainability – an ambiguous term

Sustainability is of concern of many scholars right now. Although the understanding of sustainability varies a lot, the widely accepted definition comes from so called Brundtland report [1]:

> "Sustainable development meets the needs of the present generation without compromising the ability of future generations to meet their needs."

The overall agreed consensus about this sustainability definition does not make it critic-proof. It is still criticized by various authors as being vague and unoperationalizable [2].

The concept of sustainability originally comes from forestry sector. Kasthofer defined sustainability in 1818 as [3]:

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"wenn nicht mehr jährlich darin (im Wald) Holz gefällt wird, als die Natur jährlich darin erzeugt, und auch nicht weniger"[1]

This definition already includes environmental aspects by restricting the depletion of natural resources. Furthermore, economic aspects are also included by stating that the consumption should not be less than the reproduction. In today's understanding sustainability is encapsulating besides economic and environmental aspects also social (for some scholars even institutional and/or technical) aspects.

The mainstream discourse sees sustainability consisting of tree pillars. This model is emphasizing the importance of all three aspects but it is criticized for neglecting the interrelations between the pillars. Another critic concerns the different (even contradicting) aims of these pillars [2]. Obviously more timber fall than the reproduction rate will (at least on a short term view) be beneficial for the economy but not for the nature.

A categorization of different sustainability understandings is weak and strong sustainability. The main debate is again about the perception of the relation between economic and environmental aspects.

Weak sustainability can be seen as a direct outcome of neoclassical economic stand [4]. In this view it is assumed that any process is sustainable if the output of the process has more capital than the input. The capital is considered as the sum of manufactured (man-made) capital (e.g. machines, railways, buildings etc.) and natural capital (e.g. ores, minerals, ozone layer, biodiversity etc.) [5]. The weak sustainability implies that these capitals are interchangeable.

Economic modernization theory coming from neoclassical economic tradition argues (with slight differences) that the environmental impact and economic development may produce an inverted U-shaped curve (i.e. environmental Kuznets curve) where the further economic developments will definitely help to reduce the environmental impacts. Thus, economic modernization theory does not see a fundamental conflict between modernization (or advanced capitalism) and environment [6].

Strong sustainability on the other hand opposes the idea that natural capital and manufactured capital (and also others like social capital) are interchangeable since they are not serving for the same needs. Thus, each individual capital should be preserved independently [7]. The differences between strong and weak sustainability are illustrated in Fig. 1.

The strong sustainability is aiming the box "D" whereas the weak sustainability welcomes boxes "D" and "C" provided that the quality of life (measured in terms of man made capital) is larger than degraded natural capital.

It may be appropriate to say that environmentalists favor strong sustainability as they argue that [7]:

"Although the capacity of technology, organization and culture distances humans from other species, this unique capacity is always bounded by the limits imposed by the ecological conditions."

Another view point that might be included in strong sustainability is the political economy perspective (a neo-Marxist stance) which opposes the arguments of economic modernization theories and proposes that there is a fundamental conflict between economic production and ecosystems, which implies that the expectation of the environmental Kuznets curve is not realizable. The proposed solution lies in "*restructuring of societies away from economic expansion and toward ecological sustainability*" rather than reform oriented policies [7].

[1] If annually not more timber is felt (in forest) than nature can reproduce and also not less.

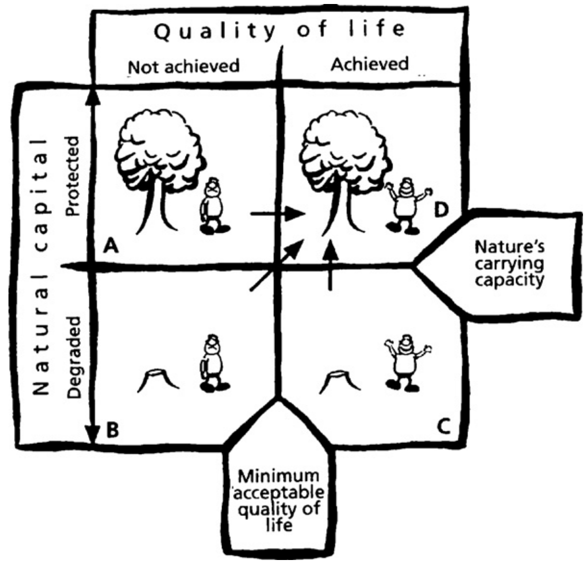

Fig. 1. Week and strong sustainability with respect to quality of life and natural capital, source: [8].

A separate debate is about the social issues whether sustainability should include inter-generational and/or intra-generational equity. As sustainability implies for an unspecified long time generally intergenerational equity is included. This is also verified by the study of expert views on sustainability [9]. The most significant outcome of this study is that sustainability is seen by the twenty one experts as a moral issue between the generations. On the other hand, not all the sustainability understandings accept intra-generational equity. A branch of political economy perspective, the world system theory, argues that intra-generational equity is desirable but not possible due to the fact that wealthy influential "*core nations*" (developed countries) are extracting resources from, and exporting wastes to "*periphery*" and "*semi-periphery*" (less developed and developing) countries [7].

2. Sustainability – a matter of measurement!

There are many different expositions of the concept sustainability as seen previously. To know how a society or a process is doing with respect to sustainability, it should be measurable. There are various sustainability measuring methods and approaches where each method needs indicators.

Many institutions develop and apply indicator sets and keep them disaggregated [e.g. 10,11,12]. This to a certain extent leads to unsatisfactory results because no aid is given on how to compare "*apples and oranges*" or to how to balance the trade-offs of opposing indicators. The results of these approaches, therefore, stay unhandy and unexpressive.

As a response to these weaknesses various "integrative" approaches to support politicians, entrepreneurs and consumers in their decisions were developed. "Integrative" approaches aim for an aggregated assessment of sustainability indicator sets which allows for summarizing and evaluative conclusions. They can be classified according to two generic methodological principles:

- the definition of threshold-values which indicators may not exceed
- the projection of multiple indicator values on a single dimension

The first principle seeks to identify naturally given (carrying capacity) or normative defined limits assuming that these limit should not violated. Prominent applications of this idea can be

Table 1
Comparison of approaches for measuring sustainability.

	Subject level		Considered aspects	Projection on a single dimension	Considered in this paper
	Society	Technology			
Indicator analysis on disaggregated basis	Yes	Yes	Various aspects depending on the research question	No	No
Guard rails	Yes	No	Various aspects depending on the research question	No	No
Minimum requirements	Yes	No	Various aspects depending on the research question	No	No
Social cost analysis	Yes	Yes	Internal costs GHG emissions Other emissions (pollutants)	Yes	Yes
Ecological footprint analysis	Yes	Yes	Land area demand GHG emissions	Yes	Yes
Exergy analysis[a]	Yes	Yes	Exergy consumption Renewability of resources	Yes	Yes
Multi criteria decision analysis[b] (MCDA)	Yes	Yes	Various aspects depending on the research question	Yes	Yes

[a] In the emergy analysis the emergy flows are quantified instead of exergy flows [15,16]. Due to the similarities with the exergy analysis, this approach is not presented separately in this paper.
[b] There are several indices that may be grouped under MCDA e.g. Human development index – HDI [17], Environmental sustainability index – ESI [18] and Environmental Performance index – EPI [19,20].

found in setting "guard rails" [13] or defining "minimum requirements" [14]. They have in common that they address sustainability of societies or energy systems rather than comparing single technologies. Moreover, they help to identify sustainable and not sustainable situations but cannot give information on the descending order from best to worst situations.

An alternative methodological principle aggregates the multiple sustainability indicators by projecting them on a single dimension. The major challenges of these approaches are to include all relevant indicators and to offer evident as well as transparent aggregation procedures. For sustainability assessment on technology, process or product level a frequently applied concept is by reducing or "projecting" several variables to one dimension. The most common one belonging to this concept probably is the expression in terms of money (especially social or external costs). Alternative approaches following the same principle which are frequently discussed in literature are the ecological footprint approach, the exergy indicator approach and the multi criteria decision analysis (MCDA).

A summary on the most common approaches for the evaluation of sustainability is given in Table 1. In this paper those approaches were chosen for in-depth assessment and exemplary application for residential heat supply technologies which fulfill two criteria: following a projective approach and focusing on single technologies.

2.1. Social cost approach

One of the first efforts to quantify sustainability was to express all impacts in terms of money [21]. The idea behind this method is that the market price of a product is indicating the scarcity of all the resources that enables the production like labour capital and materials. Thus, it makes sense to evaluate the sustainability of different processes and/or products according to their market prices. However, the problem with the evaluation of sustainability of different products and/or processes with respect to market prices is that there are some costs (i.e. external costs) that are not included in the market price. The classical example is the emissions of a power plant. The electricity producers have no incentive to reduce the emissions in a free market economy as they should behave rational. The costs of producing emissions are not covered by the producers but the costs are "*socialised*". That is all the members of the society carry the burdens (i.e. the external costs) of these emissions. Social cost calculation methods aim to include the external costs into the market prices and to reflect the (total) social cost of a product and/or a process for the society. Thus, the technology with the least social costs is the most appropriate one. As the environmental impacts can be exchanged with the cost of production in this method, it has inherently the assumption of weak sustainability.

One of the latest and solid social cost calculation methods are presented by Extern-E project [22–24]. The external costs are determined by the "*willingness to pay*" (WTP) or "*willingness to accept*" (WTA) approaches.

The advantage of this method is that the WTP and WTA values indicate the population's preferences for diverse environmental impacts [23].

One of the critic points for the proposed methodology is the underlying assumption that WTP and WTA should be the same for the same environmental impact [21]. However, the disparity between WTP and WTA approaches and its reasons are presented in [25].

2.2. Ecological footprint approach

The carrying capacity is not only important for multi variable assessment but for all sustainability evaluation methods. Wackernagel and Rees developed the concept of ecological footprint in order to compare anthropogenic use of resources and available ones in nature [26]. For this purpose they use an experiment of thought where a city is covered with a half-spherical perspex which only permits the sun light in but no other substances. The obvious result would be that such a city would not be viable. The experiment carries on and they try to find the minimum required area for a city that allows the inhabitants to survive. This approach can be extended to a nation or even to the world and the required amount of land for surviving can be compared to the available one. Thus, his method gives an indication of nature's carrying capacity.

To calculate needed area for the given standards of living (i.e. ecologic footprint) all requirements of society should be converted into fertile land. Some needs of the society are already in terms of land like the land for nutrition, buildings and roads etc. The critical part of this method is to convert social metabolism inputs and outputs (like generated emissions) into land. In the footprint analysis predominantly the green house gas (GHG) emissions are considered. The idea is that the generated GHG emissions should be absorbed by forests or sedimented to the ocean grounds in order to prevent the increase of the concentrations in the atmosphere [27,28]. Thus, the conversion of GHG emissions into land is performed simply with a conversion factor[2].

The analysis of allocated footprints for different energy sources is not uninteresting [29]. Generally, the footprint of wind turbines and photovoltaic units are generally neglected. The footprint of

[2] Factor of 1.58 t CO_2/ha for CO_2-sequestration in forests is used by Norwegian Pollution Control Authority [30]. Factor of 0.073 t CO_2/ha is calculated for carbon sedimentation in the ocean ground [27].

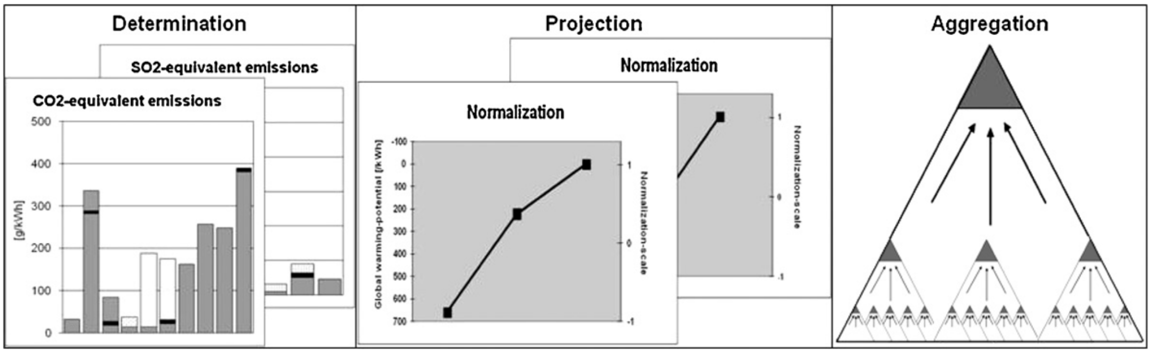

Fig. 2. Three-stage MCDA: determination, projection and aggregation.

hydropower and fuelwood are the required dam and forest area respectively. On the other hand, as the land needed to extract fossil fuels and ores are insignificantly small, the footprints associated for the non-renewable resources are neglected [29,30]. In turn, the GHG emissions from biomass and fossil fuels are added to the footprint if they are combusted. A further debateable assumption is for the footprint of nuclear energy. Its footprint is calculated as if the same amount of energy is obtained from fossil fuel sources [29]. There are many applications of this method in the literature [29–31].

2.3. Exergy approach

Exergy is defined by Kotas as [32]:

> "Exergy, as a general concept, is the maximum work potential of a given form of energy with the environment taken as the reference medium."

Mathematically, exergy per unit mass can be represented as [33]:

$$B = \Delta\left[H - T_0 S + \sum \chi_i \mu_i + \frac{v^2}{2} + gz\right] \tag{2}$$

where H is the enthalpy, S is the entropy, χ_i and μ_i are mole fraction and chemical exergy of component i respectively, v is the velocity, z is the height. T_0 is the temperature of the reference environment and Δ represent the difference with respect to the reference state for all terms of the equation. The exergy concept is relatively new in thermodynamics. Although it is not the first study for "*available energy*", the term exergy is first named by Rant in 1956. The theoretical base of exergy analysis is considerable enlarged until mid 1960s [34]. However, the link between sustainability and exergy analysis is not established until mid 90s. With the work of Cornelissen [35] exergy analysis is included in Life Cycle Assessment (LCA) and the loss of exergy in different processes is used as a sustainability indicator. Many publications on thermodynamics and sustainability follow this work [36–41]. The relevance of exergy for sustainability might be trivial at the first glance. Nearly all of the energy (and also exergy) that earth gains comes from the sun. As the energy is conserved at all times, all the incoming energy is dissipated to space in the form of low temperature heat that is with a low exergy. Thus, the exergy is depleted which is a direct outcome of second law of thermodynamics.

As the energy is conserved at all times but the exergy is depleted its loss might be used as an indicator for evaluating unsustainability of different processes. Unsustainability is defined as [37]:

> "A technological process is non-sustaining if it takes in raw materials from the ecosphere at a rate faster than the raw material is being generated, or if it produces products, typically waste, that can damage the ecological mechanisms and hence resource production."

Exergy loss is defined based on the rate of resource production of the nature and resource consumption of the society [37,38]. The nature creates with the help of sunlight fossil fuels and minerals in a relatively slow process. On the other hand, the society is using these fossil fuels and minerals at a rate that is distinctly higher than the production. Using a resource at a faster rate than its generation rate is possible only with a reserve and for a temporary time period. This will imply that a process relying on non-renewable resources cannot sustain for an unspecified long time. Therefore, only the non-renewable resources are seen as exergy loss of the nature[3].

2.4. Multi criteria decision analysis (MCDA) approach

Another common approach for aggregating various and often opposing indicators is the multi criteria decision analysis (MCDA). The purpose of this heuristic method is to reduce complexity, to serve with a solid basis for decision making and to offer transparent and reproducible procedures [42].

> "We use the expression MCDA as an umbrella term to describe a collection of formal approaches which seeks to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter" [43].

It has become quite popular to energy sciences and has been applied for energy systems in general [e.g. 44, 45, 46] and renewable energies in particular [e.g. 47, 48].

The MCDA assessments are based on – depending on the object of analysis – varying indicators, usually regarding economic, environmental and social aspects. In order to allow the comparison of indicators with different units and importance ("to solve conflicts between indicators"), during the procedure of MCDA, all values are projected to common (ordinal) scales.

Following steps can be identified for MCDA calculations (see Fig. 2):

- Determination; in a first step indicators are defined (most often by expert panels) and derived with quantitative values. This can be done by monitoring/measurement (e.g. particulate emissions in g/kWh), calculation (e.g. costs in €/kWh) or empirical surveys (e.g. local conflict potential on a 10-point likert scale).
- Projection: the derived values are expressed in different units, e.g. euros, tons or on a Likert-scale. Therefore, the values are projected

[3] As the analysis is depending on LCA studies, the consumption of non-renewable resources by renewable energy production is considered as exergy loss.

Table 2
Characteristics of a single family detached house heating demand.

	Unit	Data
Specific heat demand		
Space heating	$kWh/m^2/a$	70.0
Warm water	$kWh/m^2/a$	12.5
Total	$kWh/m^2/a$	82.5
Yearly heat demand	kWh/a	12,375
Full load hours	h	1,600
Calculated thermal capacity requirement for individual heating	kW	8

on an ordinal scale[4] by normalising them between a maximum and a minimum value. Some studies orient on the theoretical optimum (e.g. 0 g GHG emissions per kWh), realistic values (e.g. 10 g GHG emissions per kWh) or the best of the chosen technologies (e.g. 30 g GHG emissions per kWh). The latter is problematic as it produces unstable results because adding (or omitting) a technology may cause a so called rank-reversal.

- Aggregation: after the second step for each indicator ordinal figures are available. In the next step they are aggregated to one value. To meet concerns of unequal importance of different indicators, they (single values or a whole dimension) can be taken into account as weighted averages.

3. Sustainability – bridging theory and practice

Four approaches to “measure” the sustainability of technologies are introduced in the previous sections. To illustrate, the four methods are applied on the example of technology assessment for private household heat provision. For the exemplary calculation heat provision by wood pellet boilers, wood fired heating stations and natural gas fired boilers are taken into account. This helps to ground the theoretical discussion about sustainability and to bridge the regularly wide open gap between theory and practice.

3.1. Heating demand for an exemplary building

The exemplary building is a 4-person single family detached house with 150 m^2 living area in Germany. For the calculations a specific energy demand of 82.5 $kWh/m^2/a$ is assumed, which consists of the demand for space heating (70.0 $kWh/m^2/a$) and the heat demand for warm water (12.5 $kWh/m^2/a$). These assumptions lead to a yearly heat demand of 12,375 kWh (see Table 2), which is exemplary covered by three different options of heat supply technologies: (1) wood pellet fired boiler for the individual building (2) heat supply by a wood fired district heating station and (3) natural gas fired condensing boiler for the individual building.

3.2. Heat supply technologies

3.2.1. Wood pellet fired boiler for individual buildings

Wood pellet fired boilers are widely available and commercially used. For an individual building an engine performance of 8 kW is set to provide space heating and warm water. The thermal efficiency of boiler goes up to 92% but for the calculations a utilization ratio of 87% is assumed (Table 3). For the storage, especially in combination with automatically fed systems, a separate cellar room and a special discharge system is necessary. The repository for private water and buffer storage ensure a reliable and cost-effective operation [49].

3.2.2. Wood chip fired district heating station

Ligneous and culm shaped biomass especially wood chips are common renewable energy resources for the use in district heating stations. These systems are widely used in Germany. Theoretically the produced thermal energy can be used for domestic heating as well as for combined heat and power production. In this paper, the focus is on the domestic heating. The thermal capacity of the wood chip fired district heating station is set to be 5 MW. The thermal efficiency of boiler goes up to 90% and the utilization ratio is approximately 85% [50]. Generally biomass heating plants provide heat for the base load, therefore an additional system for the peak load[5] is required.

3.2.3. Natural gas fired condensing boiler for individual buildings

This heat supply technology is still the most common system for single family detached houses in Germany (48.3%, cf. [51]). Due to the condensing boiler technology, the thermal efficiency exceeds 100%[6] (utilization ratio 97%), which brings economic and environmental advantages against other fossil fuel technologies [49].

3.3. Exemplary results on sustainability of heating technologies

The detached one family house and the three supply technologies which are previously introduced are taken as the basis for exemplary calculations on “measuring” sustainable heating technologies. The following paragraphs highlight some results on their performance. The main interest is to illustrate possible information, values and insight which can be gained by applying the four methodologies.

3.3.1. Social costs analysis

Table 4 shows the results for the calculation of social costs of the different heat supply technologies. The social costs include internal (i.e. costs for heating and warm water supply) and external costs. As described in chapter 3.1 external costs consider costs from external effects as e.g. of greenhouse gas emissions and emissions of other airborne pollutants, calculating the damage attributable to each emitted pollutant. The following impact categories are distinguished:

- Impacts on human health
- Impacts on agricultural crops (loss of biodiversity, acidification, . . .)
- Impacts on building materials
- Global warming

For global warming the cost of impacts associated with an additional unit of greenhouse gas emissions are estimated. Apart from global warming health impacts of air pollutants cause the largest part of external costs. Damage cost from mortality and bronchitis due to particulate matter as well as damage costs from direct health impact of ozone are the most important factors. The direct health impacts of SO_2 and especially of NO_x are less important [23].

The yield of a cropland is affected by different emissions, mainly SO_2 and NO_x. Therefore, they are considered when the external effects of heat supply technologies are calculated. The impacts on building materials play relatively insignificant role in this context [23].

The social costs vary between about 14 and 18 ct/kWh. As Table 4 shows, the natural gas fired boiler achieves the best result for inter-

[4] There is no consensus on which scale to use. Various ordinal scales are applied, e.g. (0 to +100), (−1 to +1) or (0 to +1).

[5] In this case a natural gas boiler is assumed.

[6] The advantage of condensing boiler technology is the usability of condensation heat from steam in the exhaust. Due to the additionally gained share of condensation heat, efficiency – based on lower heating value – can be above 100%.

Table 3
Characteristics of exemplary heat supply technologies.

Heating system	Thermal capacity	Boiler efficiency	Utilization ratio	Distribution losses	Household energy demand (MWh/a)
Wood pellet fired boiler[a]	8 kW	92%	87%	0%	14.2
Wood chip fired district heating station[b]	5 MW	90%	84%[c]	8%	15.9
Natural gas fired condensing boiler[d]	8 kW	102%[e]	97%	0%	12.8

[a] [49].
[b] [50].
[c] Not including losses of for a heating grid in a residential area for detached houses.
[d] [49].
[e] The advantage of condensing boiler technology is the usability of condensation heat from steam in the exhaust. Due to the additionally gained share of condensation heat, efficiency – based on lower heating value – can be above 100%.

Table 4
Results for social cost analysis.

EUR ct_{2009}/kWh	Wood pellet fired boiler	Wood chip fired district heating station	Natural gas fired condensing boiler
Internal costs	17.12	14.22	13.17
External costs airborne pollutants	1.13	0.82	0.31
External costs GHG-emissions	0.09	0.23	0.63
Social costs	18.35	15.28	14.10
Share of external costs	6.7%	6.9%	6.6%

nal as well as for external costs. Most remarkable are the quite similar shares of the external costs for all three technologies (share of about 7% of social costs), they hardly affect the overall results. Thus, for our example, the outcome of the social cost analysis is mainly determined by the internal costs for each technology. The most expensive system in this context is the wood pellet fired boiler. Heat provision by a wood chip fired district heating station via a heat grid demands lower specific heat provision costs.

It is worth mentioning that there are controversial discussions about the external cost factors and their impacts, especially for GHG emissions. The range in the literature is between 14 €/t CO_2 (which corresponds to the actual CO_2 market price) and 55 €/t CO_2 [66]. The Stern review has even higher costs with 65 €/t CO_2 [53]. In this study the value of 25 €/t CO_2 is taken [52]. Higher values for CO_2 cost would lead to increasing shares of external costs, especially for systems based on fossil fuels.

3.3.2. Ecological footprint analysis

Provision and burning of wood pellets, wood chips and natural gas for heat supply is linked to several land area demands. In this context the ecological footprint will provide relevant sustainability criteria. The following assumptions will be taken into account for the exemplary ecological footprint calculation:

Provision of pellets and wood chips requires harvesting of forest wood residues, timber and brush-wood which are treated and conditioned. Leible et al. [54] estimate the technical potential for wood residues available in Southern German forests as about 1,300 kg (dry mass -DM) per hectare. It is assumed that this amount will be available for pellet and wood chip provision and that material loss during treatment, conditioning and transport will be 20% for pellets and 10% for wood chips. According to [30] the area needed to extract natural gas is too small to be included in the calculation. Thus area demand for natural gas provision will not be taken into account.

CO_2 will be emitted directly during burning of fossil and renewable fuels and indirectly during provision and treatment of these fuels. Indirect emissions will be accounted for fossil as well as renewable fuels. Direct emissions will only be taken into account for fossil fuels as for renewable fuels only those amounts of CO_2 are emitted which have been stored before in the lignocelluloses. For calculation of land area demand due to CO_2-emission two approaches are currently discussed. The first way is to estimate the forest land area required to sequester one ton of CO_2 emitted by burning fossil fuels. A factor of 1.58 t CO_2/ha for CO_2-sequestration in forests is used by Norwegian Pollution Control Authority [30]. The second way is based on the capacity of ocean grounds to absorb carbon. According to Krotscheck [55] the area to preserve the quantitative resources of carbon in the lithosphere is 500 m^2/a/kg carbon. This corresponds to a factor of 0.073 t CO_2/ha for carbon sedimentation in the ocean ground [27]. As a result, the ocean

Table 5
Results for ecological footprint analysis.

		Wood pellet fired boiler	Wood chip fired district heating station	Natural gas fired condensing boiler
Overall wood demand (incl. material losses)	kg(DM)/a	3,282[a]	3,366[b]	0.0
Area demand for pellet and wood chip provision	ha/a	2.52	2.59	0.0[e]
Direct and indirect (fossil based) CO_{2eq}-emissions	t CO_{2eq}/a	0.44[c]	0.33[c]	2.89[c]
Area demand for direct and indirect CO_{2eq}-sequestration in forests [d]	ha/a	0.28	0.21	1.84
Ecological footprint for heat supply	ha/a	2.81	2.80	1.84

[a] Based on household end energy demand of 14.2 MWh/a (Table 2); technical potential for wood residues 1,300 kg (DM) per hectare; 20% material losses of pellet production and provision.
[b] Based on household end energy demand of 15.9 MWh/a (Table 2); technical potential for wood residues 1,300 kg (DM) per hectare; 10% material losses of wood chip production and provision.
[c] Based on [56].
[d] 1.58 t CO_2/ha is assumed for CO_2-sequestration in forests [30].
[e] see [30].

Table 6
Exergy factors [57].

	Exergy factor (*f*)
Mechanical energy	1.0
Electrical energy	1.0
Chemical energy	1.0
Heat[a]	$1-(T/T_{amb})$

[a] Heat at temperature T compared to the ambient temperature T_{amb} (both in Kelvin).

land need indices for fossil energy use are much higher than for CO_2-sequestration in forests [28]. For this study the approach of CO_2-sequestration in forests is taken into account, as this is the most frequently used method.

The exemplary calculation shows that the ecological footprint from heat provision by natural gas fired condensing boiler results better than energy provision and utilization by wood (Table 5). The reason is that the forest area demand for pellets and wood chip provision is calculated much higher than the forest area demanded for CO_2 sequestration (i.e. especially for direct CO_2 emissions resulting from burning gas). In contrast, if waste wood is assumed to be utilized for pellet and wood chip production, this would have a neutral ecological footprint and thus alter the results of ecological footprint in favour of renewable energy technologies at the expense of fossil fuels.

3.3.3. *Exergy analysis*

As all processes in nature, the provision of space heating is also coupled with exergy losses. The exergy losses are the difference of utilized exergy in form of heat at household and the provided primary exergy. The exergies are calculated according to the below formula.

$$B = E \cdot f \tag{3}$$

where B is the exergy, E is the energy and f is the exergy factor. The exergy factors are listed for different energy sources in Table 6. The exergy factor of chemical energy is taken as 1.0 although Wall argues that "[it] may even exceed 1, due to definition of system boundaries and final states" [57].

The primary exergy requirement for the whole life cycle is calculated for the different heating technologies and presented in Table 7. This table shows that the natural gas boiler has highest exergy loss of fossil sources with 14.51 MWh/a. Wood pellet boiler and wood chip district heating station have quite low exergy loss of fossil sources with 1.59 and 1.29 MWh/a respectively although the renewable exergy utilization is high.

The most sustainable technology would be different if the alternative calculation of exergy loss is perfomed where not only the fossil exergy loss but also renewable exergy loss is considered.

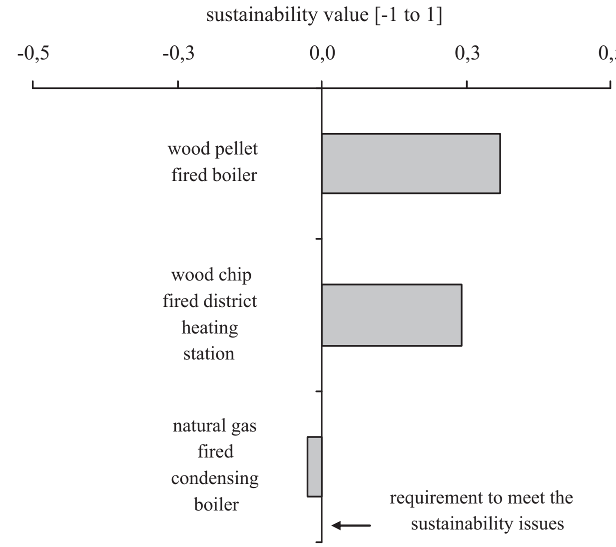

Fig. 3. Results for multi criteria decision analysis (ordinal scale).

3.3.4. *Multi criteria decision analysis (MCDA)*

As described in Section 2.4 the MCDA is based on different indicators, which are aggregated to a "sustainability value" in the final step. The following assessment is based on an indicator set (cf. annex: original and normalized indicator values) defined by a multi-disciplinary team of researchers and specifically designed for balancing sustainability of heating technologies [58].

For the projection of the different indicator values (on an ordinal scale −1 to 1), which are usually expressed in different units, a definition of extreme values is necessary. Table 8 shows the optimum and pessimum for each indicator value. The optimum is related to the theoretical optimum, respectively zero (for example cost or emission indicators). For the pessimum values different sources were analysed to identify the worst performance of a technology (highest costs, emissions etc.).

To differentiate the results and the ranking between optimum and pessimum a minimum requirement value is defined, if possible. The requirement values are derived from reduction goals of the federal government (emission indicators) or in other cases the average between optimum and pessimum.

To get to the final "sustainability value" in first step, environmental indicators (cf. Table 8, indicators 1–7), economic indicators (indicators 8–12) and social indicators are averaged within their sustainability dimension. Secondly, the three dimensions are averaged to the "sustainability value".

Fig. 3 shows the results of the MCDA for the three heat supply technologies on an ordinal scale. The "sustainability values" range between −0.02 and 0.31, so that all technologies nearly meet the

Table 7
Results for exergy analysis[a].

MWh/a	Wood pellet fired boiler	Wood chip fired district heating station	Natural gas fired condensing boiler	Sources
Primary energy	18.32	19.93	14.59	[56]
Thereof fossil sources	1.59	1.29	14.51	[56]
Thereof renewable	16.73	18.64	0.08	[56]
Primary exergy[b]	18.32	19.93	14.59	Own calculations
Thereof fossil sources	1.59	1.29	14.51	Own calculations
Thereof renewable	16.73	18.64	0.08	Own calculations
Exergy loss of fossil sources	1.59	1.29	14.51	Own calculations

[a] Another way of calculating the exergy loss is to look at the inputs and outputs of the process and identify the exergy losses in the specific heating technology (including renewable exergy loss). To perform this calculation the required exergy at the household, which is the same for all technology alternatives, should be calculated and the difference between the total exergy input and the required exergy is taken as the exergy loss indicator.
[b] It is assumed that the primary energies are purely chemical energy and have therewith the exergy factor of 1.0.

Table 8
A multi-disciplinary indicator set for heating technologies [58].

#	Indicator	Optimum	Remark	Requirement	Remark	Pessimum	Remark
1	Global warming-potential (CO_2-equivalents)	0.00 g/kWh	Theoretical optimum	219.49 g/kWh	Derived from reduction goals of the federal government	657.54 g/kWh	Worst available technology (coal furnace, cf. [56])
2	Acidification potential (SO_2-equivalents)	0.00 g/kWh	Theoretical optimum	0.24 g/kWh	Derived from reduction goals of the federal government	3.42 g/kWh	Worst available technology (coal furnace, cf. [56])
3	Ozone-forming potential (TOPP-equivalents)	0.00 g/kWh	Theoretical optimum	0.36 g/kWh	Derived from reduction goals of the federal government	3.48 g/kWh	Worst available technology (coal furnace, cf. [56])
4	Particulate emissions	0.00 g/kWh	Theoretical optimum	0.02 g/kWh	Derived from reduction goals of the federal government	1.25 g/kWh	Worst available technology (coal furnace, cf. [56])
5	Material expenditure	0.00 g/kWh	Theoretical optimum	223.87 g/kWh	Derived from reduction goals of the federal government	1,510.8 g/kWh	Worst available technology (terrestrial heat collectors, cf. [56])
6	Plant recyclability	1	“expert consultation”, ordinal scale 1 (very good)	5	Ordinal scale average	10	“expert consultation”, ordinal scale 5 (very bad)
7	Reserves of energy carriers	Endless	Theoretical optimum	152 years	Fossil energy carriers with longest range (coal: 152a, cf. BMWI 2008)	0 years	Theoretical value
8	Annual capital costs	0.0 EUR/a	Theoretical optimum	1,132.5EUR/a	Average between optimism and pessimism	2265EUR/a	Average of solar district heating, pilot projects [59]
9	Annual fixed operating maintenance costs	0.0 EUR/a	Theoretical optimum	242.7EUR/a	Average between optimism and pessimism	485.31EUR/a	Worst available technology (veg-oil BHKW, own calculations)
10	Annual fuel costs	0.0 EUR/a	Theoretical optimum	377.5EUR/a	Average between optimism and pessimism	755EUR/a	Worst available technology (night storage heater, own calculations)
11	Security of supply (general) [a]	0%	Theoretical optimum	50%	Average between optimism and pessimism	100%	Theoretical value
12	Development and volatility of fuel prices	0%	Theoretical optimum	Up to 128.79%	Average between optimism and pessimism	Up to 257.58%	[60–62]
13	Share of the heating energy costs in the household income	0.0%	Theoretical optimum	10.9%	Portion of the reference system (gas-condensing boiler) heating energy costs in the household income	17.3%	Worst available technology (solar district heating, own calculations)
14	Potential for conflicts in the neighborhood	1	“expert consultation”, ordinal scale 1 (very good)	5	Ordinal scale average	10	“expert consultation”, ordinal scale 10 (very bad)
15	Alternative use of primary energy carriers	So far not considered due to data availability					
16	Local impact on the residents[b]	1	“expert consultation”, ordinal scale 1 (very good)	5	Ordinal scale average	10	“expert consultation”, ordinal scale 10 (very bad)
17	Accident and health risks	1	“expert consultation”, ordinal scale 1 (very good)	5	Ordinal scale average	10	“expert consultation”, ordinal scale 10 (very bad)
18	Social benefit	1	“expert consultation”, ordinal scale 1 (very good)	5	Ordinal scale average	10	“expert consultation”, ordinal scale 10 (very bad)

[a] Include the sub-indicators “dependence on imports” and “concentration of imports on region of origin”
[b] Include the sub-indicators noise, traffic, exhalation and aesthetics.

Table 9
Synopsis on projective approaches for measuring sustainability.

	Social costs	Ecological footprint	Exergy assessment	Multi criteria decision analysis
Short description	Balancing all costs and benefits in terms of monetary values.	Projection of all efforts/expenses to the dimension of land.	Aggregation to depleted exergy	Reduces multiple indicators to a defined scale
Practical application	Yes	Yes	No	Yes
Scope	Technology-related	Various spatial levels[a] and technology-related	Technology-related	Technology-related
Number of aggregated indicators	Medium	Medium	Low	High
General understanding of sustainability	Weak	Strong	Strong	Weak
Carrying capacity	No	Yes	No	No
Vividness/traceability	Medium	High	Low	High–medium
Advantages	High evidence and wide acceptance of monetary units	Illustrative quality	Highly ambitious theoretical concept	Offers a clear hierarchy of technologies
Disadvantages	Reduction to money and difficulties in monetarization[b]	Focus land area demand neglecting economic parameters	Impracticable unit neglecting economic parameters	Choice and weighting of indicators is criticized to be arbitrary
Results of exemplary calculations	Monetary values (EUR ct_{2009}/kWh)	Carrying capacity (ha/a)	Discrepancy to society's maximum potential (MWh/a)	Ordinal scale (−1 to +1)
	Natural gas fired condensing boiler (14.10)	Natural gas fired condensing boiler (1.84)	Wood chip fired district heating station (1.29)	Wood pellet fired boiler (0.31)
	Wood chip fired district heating station (15.28)	Wood chip fired district heating station (2.80)	Wood pellet fired boiler (1.59)	Wood chip fired district heating station (0.24)
	Wood pellet fired boiler (18.35)	Wood pellet fired boiler (2.81)	Natural gas fired condensing boiler (14.51)	Natural gas fired condensing boiler (−0.02)

[a] The practical application of ecological footprint covers more or less all spatial levels, such as local, regional, national and worldwide [26,31,63,64].
[b] Discount rate, timeframe, wtp vs. wta, uncertainties of estimating CO_2 costs.

sustainability requirement which is defined as zero. The wood pellet fired boiler as well as the wood chip fired district heating station achieve a considerably better result then the natural gas fired boiler. Although they by far did not reach the theoretical optimum of 1 they reach a high score for the indicators global warming potential, reserves of energy carriers, security of supply as well as accident and health risks. In contrast to these values the results of economic indicators are relatively unfavourable.

The results of natural gas fired boiler are poor mainly due to the indicators of energy carrier reserves, fuel costs and conflict potentials. But also positive results were achieved, for example the indicators of particulate emissions as well as material and capital expenditure, which improve the results. With a "sustainability value" of −0.02 the natural gas fired boiler is, therefore, rated as almost sustainable.

4. Choosing sustainability? – a discussion

In this section, four projective methods for measuring sustainability of technologies (social costs, ecologic footprint, exergy and multi criteria decision analysis) are compared and contrasted. Table 9 presents the considered aspects. The four methods "produce" distinct, sometimes even opposing results. Notwithstanding the methods can be assigned to weak and strong sustainability understandings, it is interesting to see that the differences in results cannot be explained with these categories (Table 9). The four approaches on the one hand can solve the inherent problem of disaggregated indicator sets – they offer integrated results – on the other hand they come along with their own weaknesses:

- Exclusion of social aspects and problems of monetarization (social costs)
- Focus on nature's carrying capacity for land area and neglecting other important environmental issues and economic aspects (ecological footprint)
- Reference to a very theoretic concept and projection on a very uncommon, impracticable unit (exergy assessment)
- Arbitrariness of choosing and weighting indicators, which is based on expert opinions (multi criteria decision analysis)

Moreover, except of MCDA none of these methods includes social issues such as inter-generational and/or intra-generational equity explicitly. However, the footprint analysis might be extended to include intra-generational equity if different average footprint analyses of different countries are compared. The results of several studies clearly show that there is a huge gap between footprints of different nations [e.g. 29]. Although there is no such a study in the literature, such an analysis might also be done for exergy losses and external costs of nations.

As the market economy is based on rational behaving individuals, it is very important to include costs into sustainability analysis, which is one of the strong sides of social cost method. Another plus is that as the comparison is in monetary terms it is understandable and comparable. However, the conversion of environmental effects to monetary units might be problematic if the processes in different countries (e.g. an industrial and a developing country) are to be compared since the willingness to pay approach is clearly depended on the average purchasing power of the people in that country. Furthermore, the underlying assumption that WTP and WTA should be the same for the same environmental impact is often criticized [e.g. 25].

The strength of footprint analysis is that the nature's carrying capacity can be calculated and one can see how much the nature is stressed by human activities. Another advantage of footprint analysis is that the results are in terms of land area which is easily understandable also for non-scientific people. The weakness, on the other hand, is that it considers mainly the GHG emissions, since there is no solid way to convert other emissions into land. Moreover, the conversion methods of different energy sources (like fossil fuels) to land might be seen critical. If one would like to compare the ecological footprint of biofuels and conventional ones, the results are quite unsatisfactory for the biomass based fuels [30, Table 4]. This is for the fact that the method does not take the resource depletion of fossil fuels into account since the required land for that is negligible.

The strength of exergy analysis is the scientific sound calculation method and the determination of resource depletion. With the method of Dewulf and Langenhove [37], the resource depletion can be combined with the exergy loss of environment and one can get one indicator for different industrial processes. The weak side of this method is that the economic considerations are not included in the analysis at all.

The MCDA outweigh the other methods by the number of economic, environmental and social indicators which are considered. Moreover, it produces a clear ranking of technologies by implementing transparent calculation procedures and can therefore provide a good basis for decision making. This has made the method quite popular and supported its application to the field of (renewable) energies. In turn, it has received much more criticism than the other methods. Due to its heuristic character and its relevance on expert opinions, to a certain extent, it remains fragile for harsh criticism such as: "*MCDA is arbitrary*". The results of MCDA can certainly be enhanced by using solid and representative empirical values (on weightings) reflecting consensus.

Of course, sustainability can hardly be chosen by just adopting one of the presented approaches. To do so an intensive discourse is required. And besides obvious weaknesses and the insolubility of the decision-making paradoxon [65], the applied methods can help to come closer to identify sustainable technologies given that they are regarded as heuristic methods or as "educated guesses"and not as the ultimate solution in identifying sustainable technologies. Especially if they are applied complementary they may help to expose different perspectives on technologies and foster the discourse on sustainability.

The main task of these approaches, however, is to facilitate transparent and reproducible procedures. By doing this, they make explicit what often stays implicit (normative evaluations) and stimulate an exchange on theory and practice of sustainable technologies as well as the "correct" input values. The discussed approaches – to a certain extent – account to different "rationalities" or "cultures". But applying them complementary may, however, help to make the concept of sustainability more operationalizable and less arbitrary as the discourse on sustainability, its indicators and understandings is fostered.

Appendix A. Annex original and normalized indicator values for MCDA [58]

Ser. no.	Indicator	Wood pellet fired boiler		Wood chip fired district heating station		Natural gas fired condensing boiler	
		Original value	Normalized value	Original value	Normalized value	Original value	Normalized Value
1	Global warming-potential (CO_2-equivalents)	31.86 g/kWh	0.85	85.31 g/kWh	0.61	248.74 g/kWh	−0.07
2	Acidification potential (SO2-equivalents)	0.42 g/kWh	−0.06	0.41 g/kWh	−0.05	0.14 g/kWh	0.43
3	Ozone-forming potential (TOPP-equivalents)	0.55 g/kWh	−0.06	0.50 g/kWh	−0.05	0.29 g/kWh	0.18
4	Particulate emissions	0.070 g/kWh	−0.04	0.030 g/kWh	−0.01	0.007 g/kWh	0.69
5	Material expenditure	122.71 g/kWh	0.45	141.42 g/kWh	0.37	80.06 g/kWh	0.64
6	Plant recyclability	3.9 [ordinal scale 1–10]	0.53	4.2 [ordinal scale 1–10]	0.46	4.0 [ordinal scale 1–10]	0.50
7	Reserves of energy carriers	In principle endless	1.00	In principle endless/60 years[a]	0.68	60 years	−0.61
8	Annual capital costs	849.55 EUR/a	0.25	837.00 EUR/a	0.26	554.36 EUR/a	0.51
9	Annual fixed operating maintenance costs	479.36 EUR/a	−0.98	125.00 EUR/a	0.48	303.28 EUR/a	−0.25
10	Annual fuel costs	597.14 EUR/a	−0.58	580.00 EUR/a	−0.54	667.96 EUR/a	−0.77
11	Security of supply (general)[b]	100%	1.00	100.00%/60.75%[a]	0.76	60.75%	−0.22
12	Development and volatility of fuel prices	50.08%/1.46%	0.74	55.85%/1.70%	0.16	39.42%/2.91%	0.08
13	Share of the heating energy costs in the household income[c]	5.10%/11.00%	−0.01	4.8%/10.3%	0.05	5.1%/10.9%	0.00
14	Potential for conflicts in the neighborhood	2.0 [ordinal scale 1–10]	0.67	3.4 [ordinal scale 1–10]	0.20	9.0 [ordinal scale 1–10]	−0.83
15	Alternative use of primary energy carriers	Not considered due to data availability					
16	Local impact on the residents[d]	3.0 [ordinal scale 1–10]	0.63	7.4 [ordinal scale 1–10]	−0.08	4.3 [ordinal scale 1–10]	0.44
17	Accident and health risks	2.8 [ordinal scale 1–10]	0.69	2.7 [ordinal scale 1–10]	0.66	8.4 [ordinal scale 1–10]	−0.20
18	Social benefit[e]	5.5/8.0 [ordinal scale 1–10]	0.30	5.0/8.0 [ordinal scale 1–10]	0.25	2.0/0.0 [ordinal scale 1–10]	−0.38

[a] Back-up system.
[b] Include the sub-indicators "dependence on imports" and "concentration of imports on region of origin."
[c] The income of an average household and the income of an "working poor" family" were presented. The values for working poor are considered.
[d] Include the sub-indicators noise, traffic, exhalation and aesthetics.
[e] Include the sub-indicators "innovation potential" and "impact on employment."

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